Optical Readout Time Projection Chamber (O-TPC) New Technology for Studies in Nuclear Astrophysics

Moshe Gai

1. **The Problem: C/O ratio in Helium Burning**
   (Who cares? the shattered hopes/illusions)

2. **The Solution: O-TPC**
   (Who will do it? and where?)

PTB Braunschweig, 17 May 2005

The Laboratory for Nuclear Science
At Avery Point

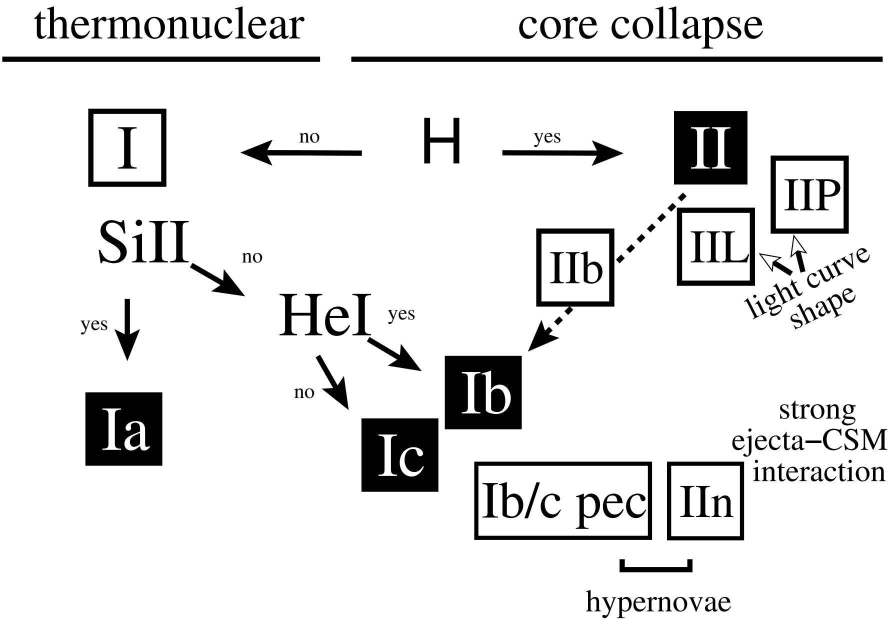
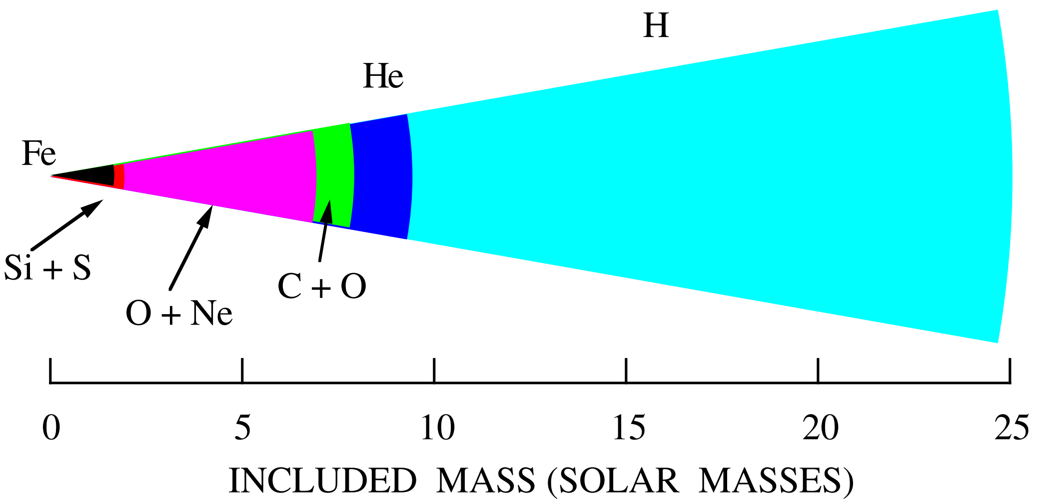
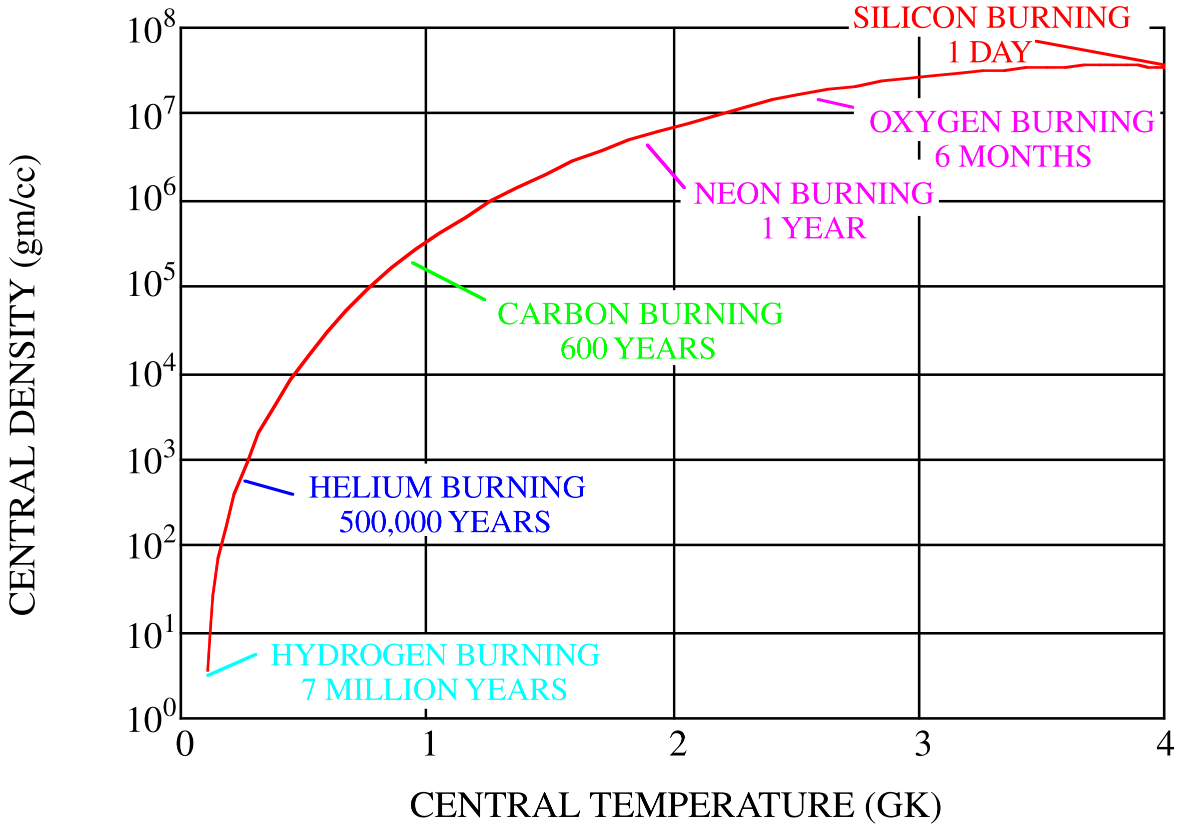
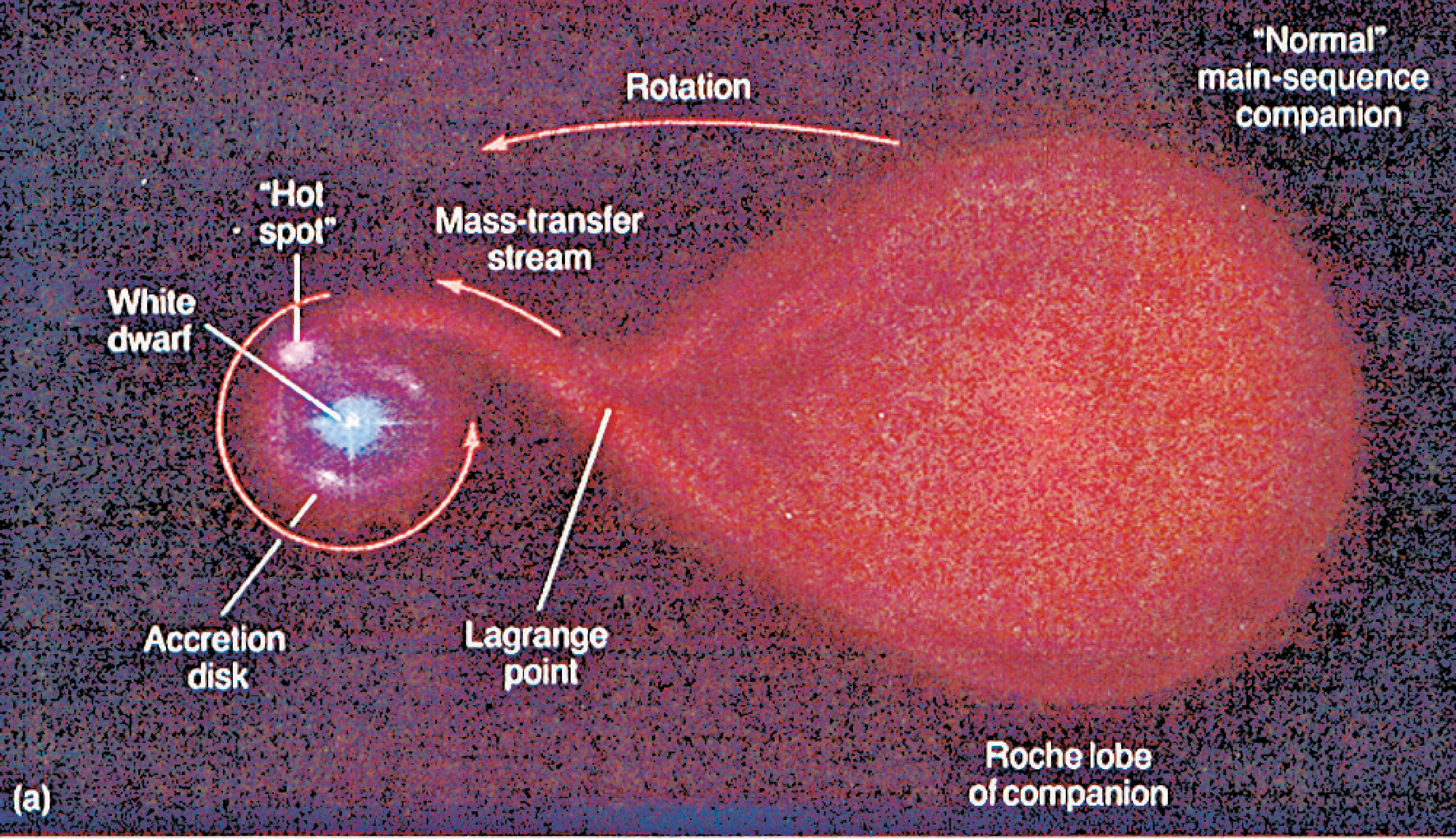


Fig. 1. The current classification scheme of supernovae. Type Ia SNe are associated with the thermonuclear explosion of accreting white dwarfs. Other SN types are associated with the core collapse of massive stars. Some type Ib/c and IIn SNe with explosion energies $E > 10^{52}$ erg are often called hypernovae.





Brown & Bethe - 1985 (x10)


"Normal" main-sequence companion
Rotation
"Hot spot"
Mass-transfer stream
White dwarf
Accretion disk
Lagrange point
Roche lobe of companion
(a)

Barely Existing Things/ Jewan Kim, 1993

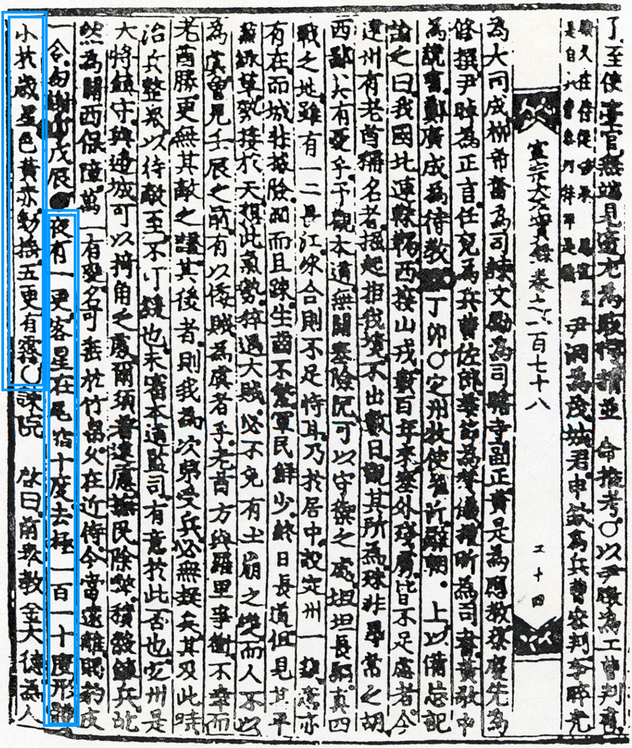
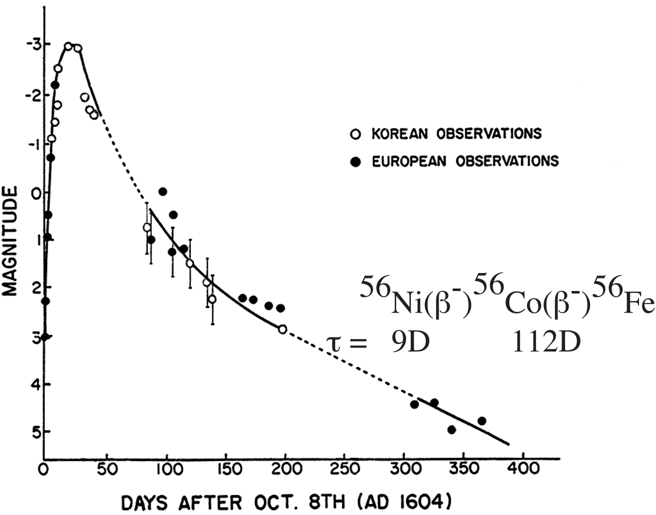


그림 3 손님별(초신성)을 발견한 선조조의 왕조실록의 기록.

객성을 발견한 당시의 생생한 기록이 있다. 즉 〈夜有一更客星在尾宿十度去極一百一十度形體小於歲星色黃赤動搖五更有霧〉(초저녁 손님별이 미수 10도 거극 1백10도 자리에 있었는데 목성보다 작고 적황색 빛깔로 흔들리고 있었으며 이른 새벽녘에는 안개가 끼었다)로 적고 있다. 『조선왕조실록』은 그뒤 약 1년 동안 객성의 관측을 상세히 기

夜有一更	10 PM at night
客 星	Guest star
在尾宿十度	10 deg in the Ophiuchus
去極百十度	110 deg in the Latitude
形体小於歲星	dimmer than Jupiter
色黄赤動搖	Yellowish red and shaking
五更有霧	4 am there was mist



$^{56}Ni(\beta^-)^{56}Co(\beta^-)^{56}Fe$

$\tau =$ 9D 112D

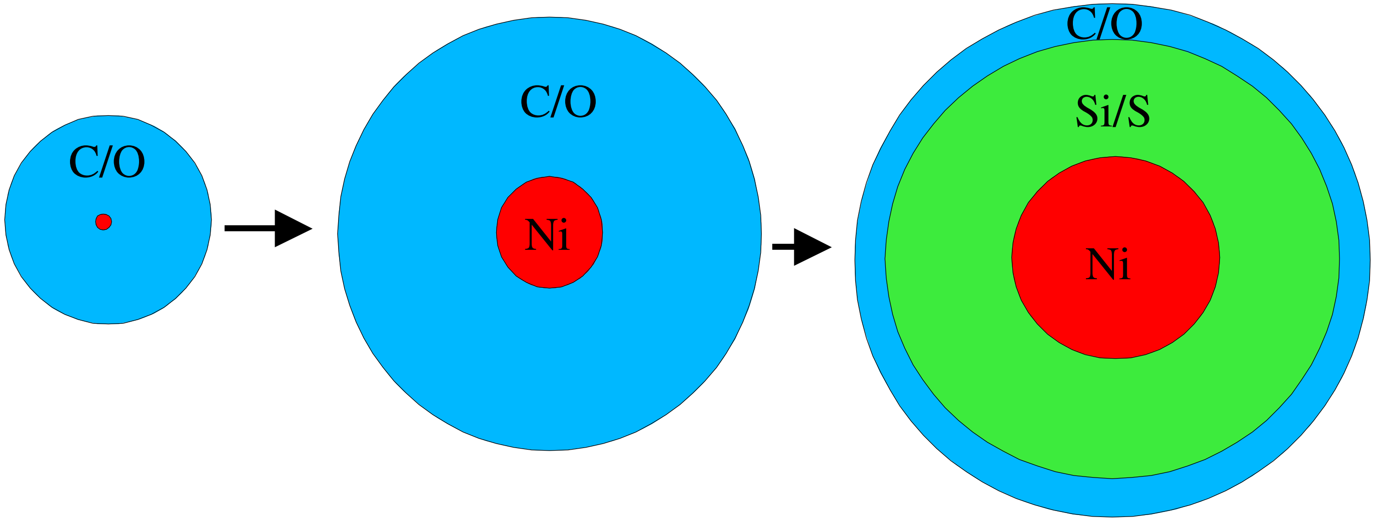
그림 3

Explosion of a White Dwarfs (Defl., Delayed Det. & Merger)

Initial WD

Deflagration phase(2...3sec)
preexpansion of the WD

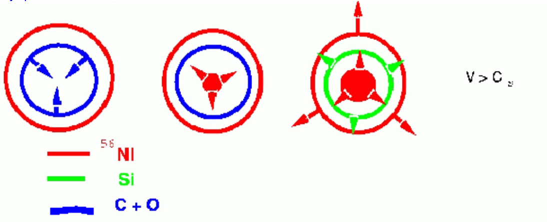
Detonation phase (0.2...0.3 sec)
hardly any time for further expansion

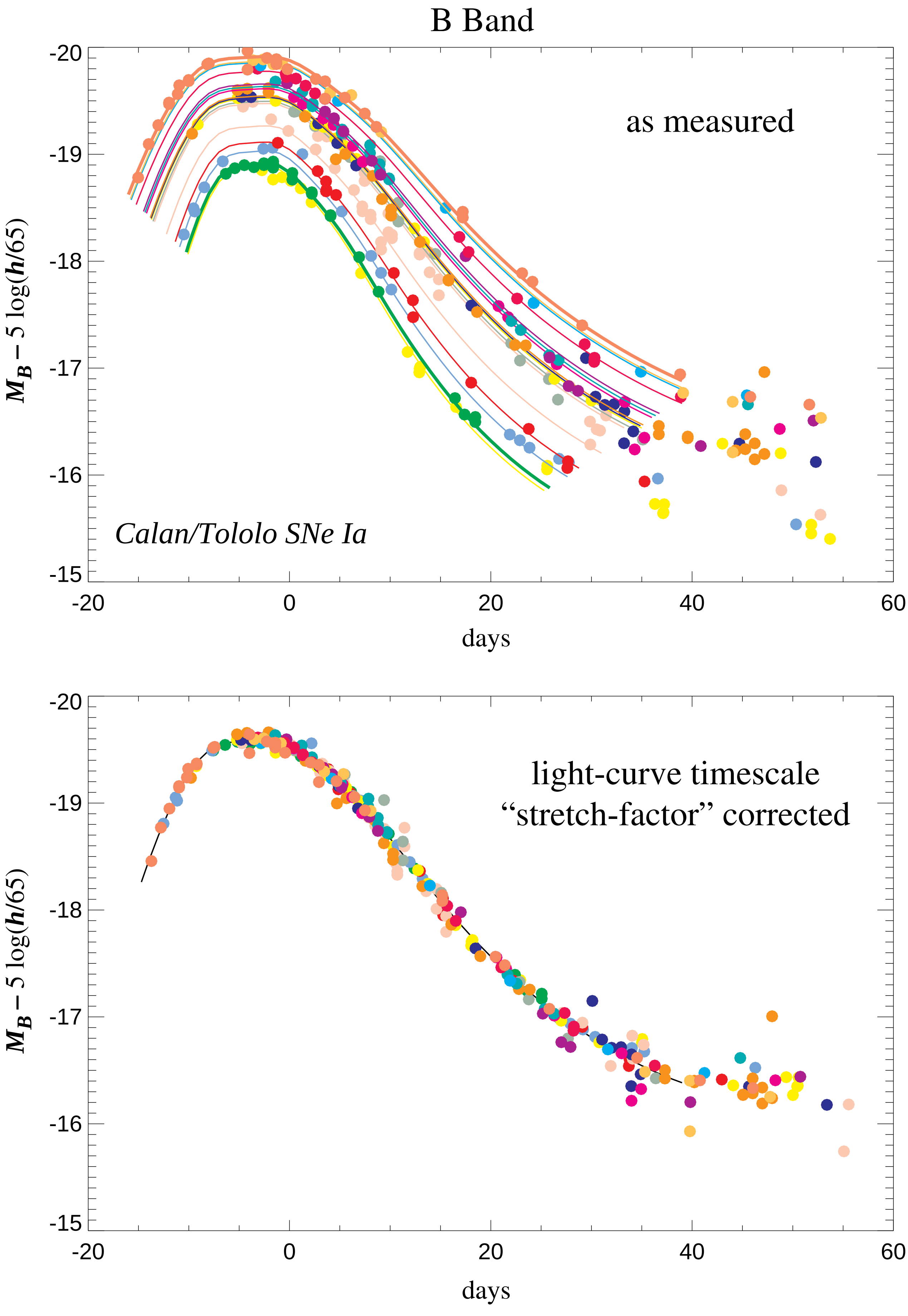


Deflagration: Energy transport by heat conduction over the front, v <<v(sound)=> ignition of unburned fuel (C/O)
Detonation: ignition of unburned fuel by compression, v = v(sound)

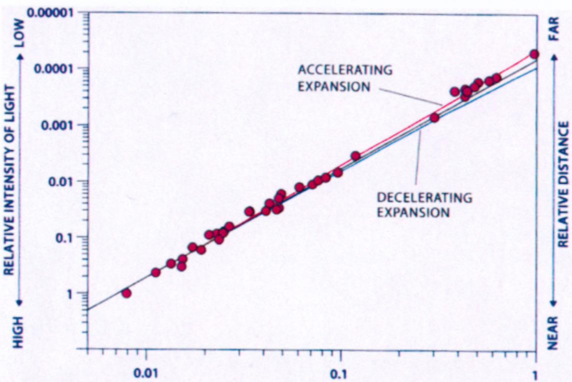
Rem1: Pre-expansion depends on the amount of burning. The rate of burning
hardly changes the final structure for DD-models (Dominguez et al. ApJ 528, 590)

Rem.2: HeDs (sub-MCh) - disagree with LCs and spectra
(Nugent et al. 96, Hoeflich et al. 96)





Kim, *et al.* (1997)


0.00001
0.0001
0.001
0.01
0.1
1
LOW
RELATIVE INTENSITY OF LIGHT
HIGH
FAR
RELATIVE DISTANCE
NEAR
ACCELERATING EXPANSION
DECELERATING EXPANSION
0.01
0.1
1

Red Shift (Z)

Peter Hoeflich (2002)

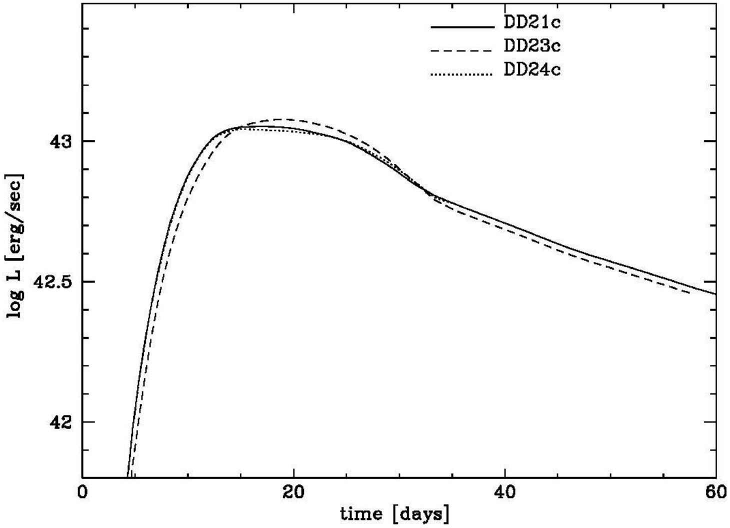
INFLUENCE ON LIGHT CURVES (0-60 Days)

DD21c: C/O=1/1; Z=0.02 (solar)

DD23c: C/O=2/3; Z=0.02 (solar)

DD24c: C/O=1/1; Z=0.0067 (solar/3)

Bolometric Light Curves



C/O Ratio of the WD

- Maxima ≈ 2-3 days later (i.g. 1-5 days)
- Peak to 'Tail' ratio changes by $\approx 0.3^m$

Metalicity Z - negligible

OFF SET in M(dM15)

$dM(V) \simeq 0.1\, dt(rise)$

The chlorine detector must be maintained in low-level operation until the chlorine and gallium detectors can be operated at full level simultaneously. Otherwise endless conjecture concerning time variations in the solar neutrino flux will ensue. Moreover, the results of the gallium observations may uncover information that has been overlooked in the past chlorine observations.

The CNO cycle operates at the higher temperatures which occur during hydrogen burning in main sequence stars somewhat more massive than the sun. This is the case because the CNO cycle reaction rates rise more rapidly with temperature than do those of the *pp* chain. The cycle is important because ^{13}C, ^{14}N, ^{15}N, ^{17}O, and ^{18}O are produced from ^{12}C and ^{16}O as seeds. The role of these nuclei as sources of neutrons during helium burning is discussed in Sec. V.

V. THE SYNTHESIS OF ^{12}C AND ^{16}O AND NEUTRON PRODUCTION IN HELIUM BURNING

The human body is 65% oxygen by mass and 18% carbon, with the remainder mostly hydrogen. Oxygen (0.85%) and carbon (0.39%) are the most abundant elements heavier than helium in the sun and similar main sequence stars. It is little wonder that the determination of the ratio ^{12}C/^{16}O produced in helium burning is a problem of paramount importance in Nuclear Astrophysics. This ratio depends in a fairly complicated manner on the density, temperature, and duration of helium burning, but it depends directly on the relative rates of the $3\alpha \rightarrow {}^{12}$C process and the ^{12}C$(\alpha,\gamma)^{16}$O process. If $3\alpha \rightarrow {}^{12}$C is much faster than ^{12}C$(\alpha,\gamma)^{16}$O, then no ^{16}O is produced in helium burning. If the reverse is true, then no ^{12}C is produced. For the most part the subsequent reaction ^{16}O$(\alpha,\gamma)^{20}$Ne is slow enough to be neglected.

There is general agreement about the rate of the $3\alpha \rightarrow {}^{12}$C process, as reviewed by Barnes (1982). However there is a lively controversy at the present time about the laboratory cross section for ^{12}C$(\alpha,\gamma)^{16}$O and about its theoretical extrapolation to the low energies at which the reaction effectively operates. The situation is depicted in Figs. 4, 5, and 6, taken with some modification from Langanke and Koonin (1983), Dyer and Barnes (1974), and Kettner *et al.* (1982). The Caltech data obtained in the Kellogg Laboratory is shown as the experimental points in Fig. 4, taken from Dyer and Barnes (1974), who compared their results with theoretical calculations by Koonin, Tombrello, and Fox (1974). The Münster data are shown as the experimental points in Fig. 5, taken from

Helium Burning:

$$3\alpha \rightarrow {}^{12}C \text{ Known}$$

$$\alpha + {}^{12}C \rightarrow {}^{16}O \quad ???$$

$$\boxed{C/O = ?}$$

$${}^{12}C(\alpha,\gamma){}^{16}O \ (E_{cm} = 300 \text{ keV})$$

$$\sigma(\alpha,\gamma) = S/E \times e^{-2\pi\eta}$$

$$(\eta = e^2 Z_1 Z_2/\hbar\upsilon = Z_1 Z_2 \alpha/\beta)$$

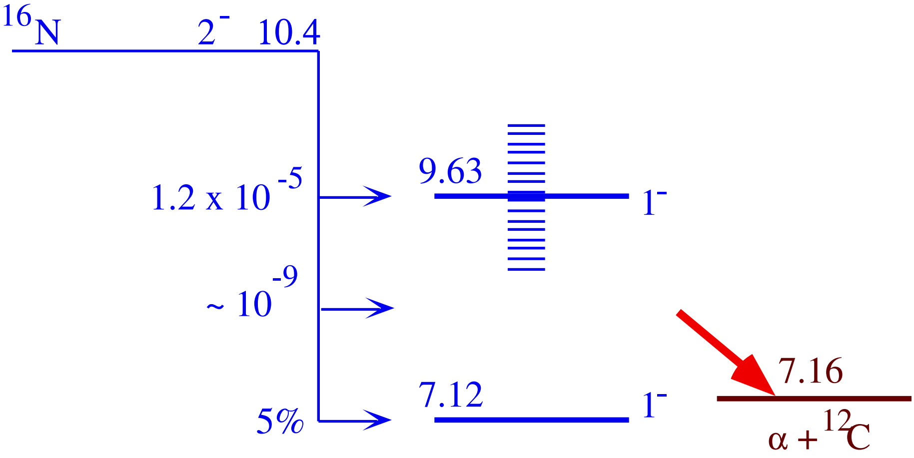
Astrophysical Cross Section Factor (P and D waves)

$$\boxed{\begin{array}{c} S_{E1}(300) \\ S_{E2}(300) \\ \pm 15\% \end{array}}$$

Notre Dame - 2002

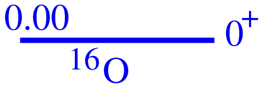
ratios of the excitation function for $\theta_{\mathrm{lab}} = 84.0°$ relative to the one at $\theta_{\mathrm{lab}} = 58.9°$ and a fit to this function.

The best fit for the reduced width amplitude of the 2^+ subthreshold state occurred for $\gamma_{12} = 0.47$ MeV$^{1/2}$, with $\gamma_{11} = 0.27$ MeV$^{1/2}$ for the subthreshold 1^- state for the single channel program. Identical results were obtained in the multichannel program (both $a = 5.5$ fm). To obtain an error estimation, fits were obtained for values of γ_{12} from 0.2 to 0.60 MeV$^{1/2}$, with all other parameters being allowed to vary. The resulting χ^2 curve is shown in Fig. 2(a). The same approach was used to scan γ_{11} from 0 to 0.60 MeV$^{1/2}$ for the 1^- state. A 1σ uncertainty of $\gamma_{12} = 0.47 \pm 0.06$ MeV$^{1/2}$, and $\gamma_{11} = 0.27^{+0.11}_{-0.27}$ MeV$^{1/2}$ was calculated with the previously established [2] guideline $\chi^2 < \chi^2_{\min} \pm 9\chi^2_{\nu}$. A list of the best fit parameters is presented in Table I. The best fit has a χ^2_{ν} of approximately 1.66. Deviations from an ideal fit occur at resonances with widths in the keV range where the sensitivity to target effects and beam energy calibration is from ^{12}C$(\alpha, \gamma)^{16}$O and ^{16}N data [2]. This analysis leads to a value of $S_{E1}(300) = 80 \pm 20$ keV b, and $S_{E2}(300) = 49^{+7}_{-9}$ or 58^{+8}_{-11} keV b, depending on the sign of the $E = 4.39$ MeV 2^+ resonance γ width amplitude relative to that for direct capture and the subthreshold resonance. As this interference sign is unknown, the two results are averaged and errors include the limits on both measurements, yielding $S_{E2}(300) = 53 \pm 13$ keV b. With the full range of a allowed here, the final result is $S_{E2}(300) = 53^{+13}_{-18}$ keV b. In this analysis destructive interference between the ground state direct capture and the tail of the subthreshold 2^+ resonance has been employed. This is justified by a total decrease in χ^2 of nearly 300 between the destructive and constructive options, largely due to the γ-angular distributions of Refs. [5] and [7]. However, additional angular distributions would be desirable, as the constructive option leads to 92 and 102 keV b, respectively, for $S_{E2}(300)$. The data set of Ref. [25] is unfortunately not available to the authors.



Enhancement: (I) W_0^5

(II) Matrix Elements



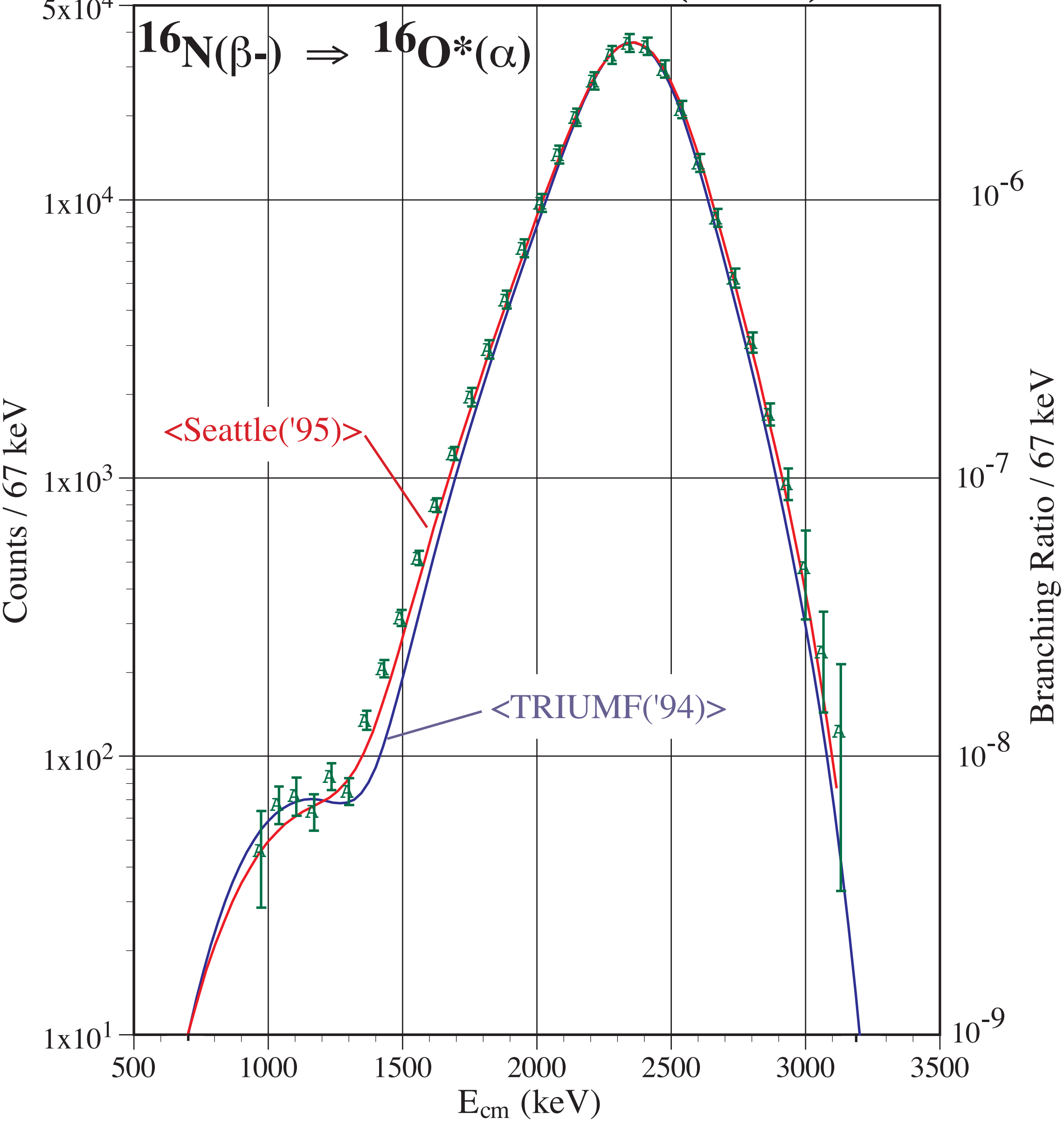
$^{12}C(\alpha,\gamma)^{16}O$: $\sigma = \sigma_{E1} + \sigma_{E2}$

$^{16}N(\beta^-)^{16}O^*$: $\sigma = \sigma_{E1} + \cancel{\sigma_{E3}}$

β^- Selection Rules: $\Delta J = 0,1 \quad \Delta\pi = +$

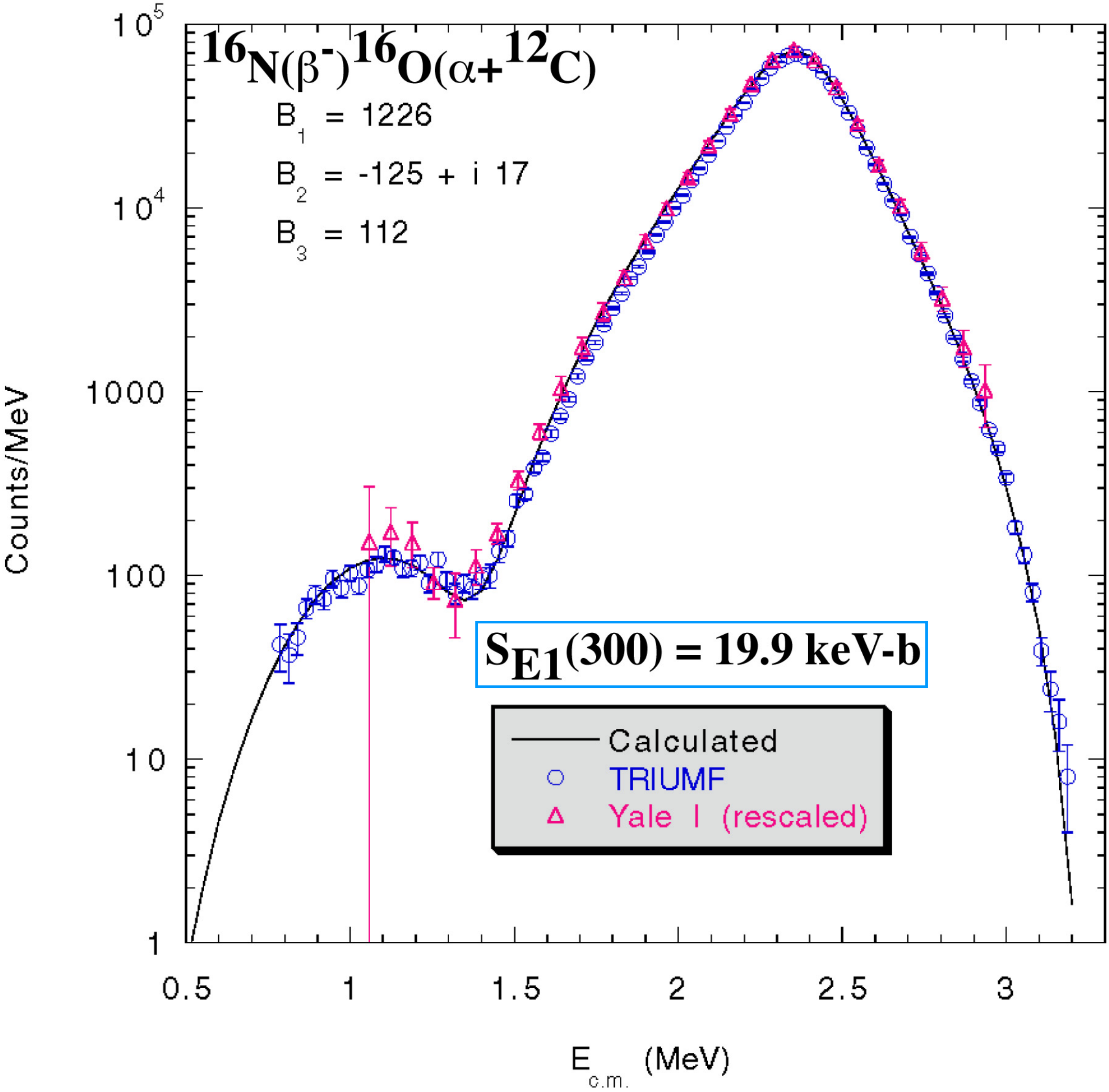
$2^- \longrightarrow 1^-$ or 3^-

Yale-UConn (1995)



TRIUMF(94): $S_{E1}(300) = 81 \pm 21$ keV-b

G.M. Hale; Nucl. Phys. A621(1997)177c



$S_{E1}(300) = 19.9$ keV-b

Eur. Phys. J. A **11**, 357–370 (2001)

THE EUROPEAN
PHYSICAL JOURNAL A

The E1 capture amplitude in $^{12}C(\alpha, \gamma_0)^{16}O$

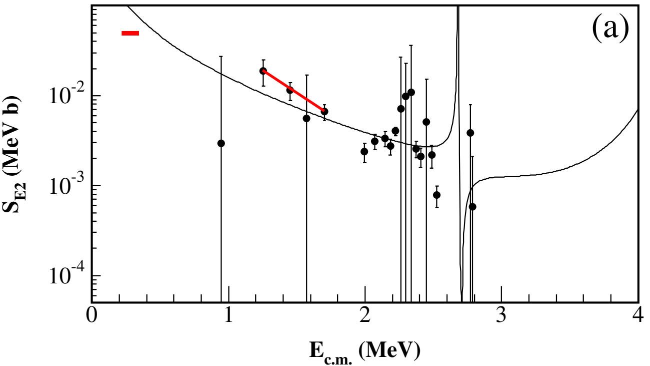
L. Gialanella[1], D. Rogalla[1], F. Strieder[1], S. Theis[1], G. Gyürki[5], C. Agodi[4], R. Alba[4], M. Aliotta[1,a], L. Campajola[2], A. Del Zoppo[4], A. D'Onofrio[3], P. Figuera[4], U. Greife[1], G. Imbriani[2], A. Ordine[2], V. Roca[2], C. Rolfs[1,b], M. Romano[2], C. Sabbarese[3], P. Sapienza[4], F. Schümann[1], E. Somorjai[4], F. Terrasi[3], and H.P. Trautvetter[1]

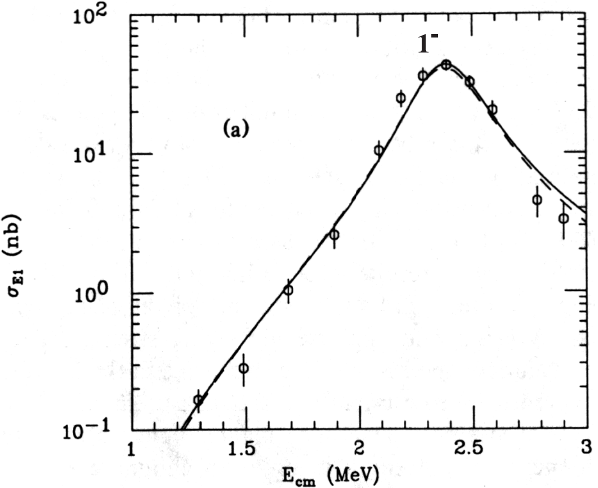
[1] Institut für Physik mit Ionenstrahlen, Ruhr-Universität Bochum, Bochum, Germany
[2] Dipartimento di Scienze Fisiche, Università Federico II, Napoli and INFN, Napoli, Italy
[3] Dipartimento di Scienze Ambientali, Seconda Università di Napoli, Caserta and INFN, Napoli, Italy
[4] Laboratori Nazionali del Sud, INFN, Catania, Italy
[5] Atomki, Debrecen, Hungary

Received: 6 June 2001 / Revised version: 9 July 2001
Communicated by Th. Walcher

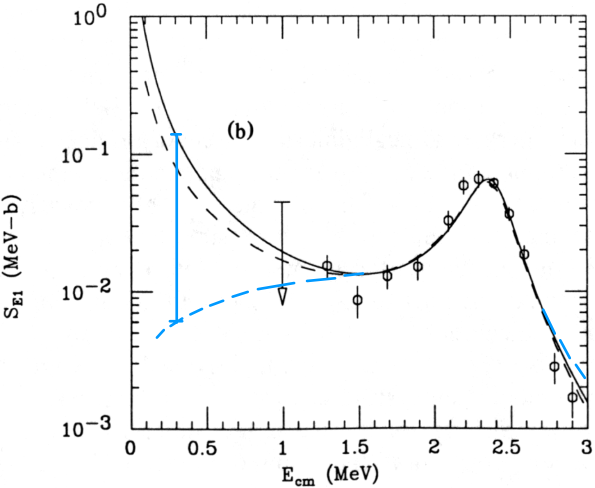
Abstract. An excitation function of the ground-state γ_0-ray capture transition in $^{12}C(\alpha, \gamma)^{16}O$ at $\theta_\gamma = 90°$ was obtained in far geometry using six Ge detectors, where the study of the reaction was initiated in inverse kinematics involving a windowless gas target. The detectors observed predominantly the $E1$ capture amplitude. The data at $E = 1.32$ to 2.99 MeV lead to an extrapolated astrophysical S factor $S_{E1}(E_0) = 90 \pm 15$ keV b at $E_0 = 0.3$ MeV (for the case of constructive interference between the two lowest $E1$ sources), in good agreement with previous works. However, a novel Monte Carlo approach in the data extrapolation reveals systematic differences between the various data sets such that a combined analysis of all available data sets could produce a biased estimate of the $S_{E1}(E_0)$ value. As a consequence, the case of destructive interference between the two lowest $E1$ sources with $S_{E1}(E_0) = 8 \pm 3$ keV b cannot be ruled out rigorously.

PACS. 24.10.-i Nuclear-reaction models and methods – 25.40.-h Nucleon-induced reactions

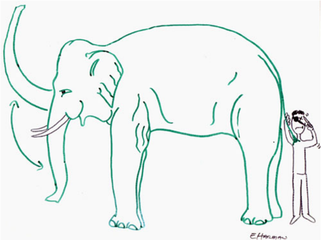

(a)
S_{E2} (MeV b)
10^{-2}
10^{-3}
10^{-4}
0
1
2
3
4
$E_{c.m.}$ (MeV)



10^2
10^1
10^0
10^{-1}
1^-
(a)
σ_{E1} (nb)
1
1.5
2
2.5
3
E_{cm} (MeV)

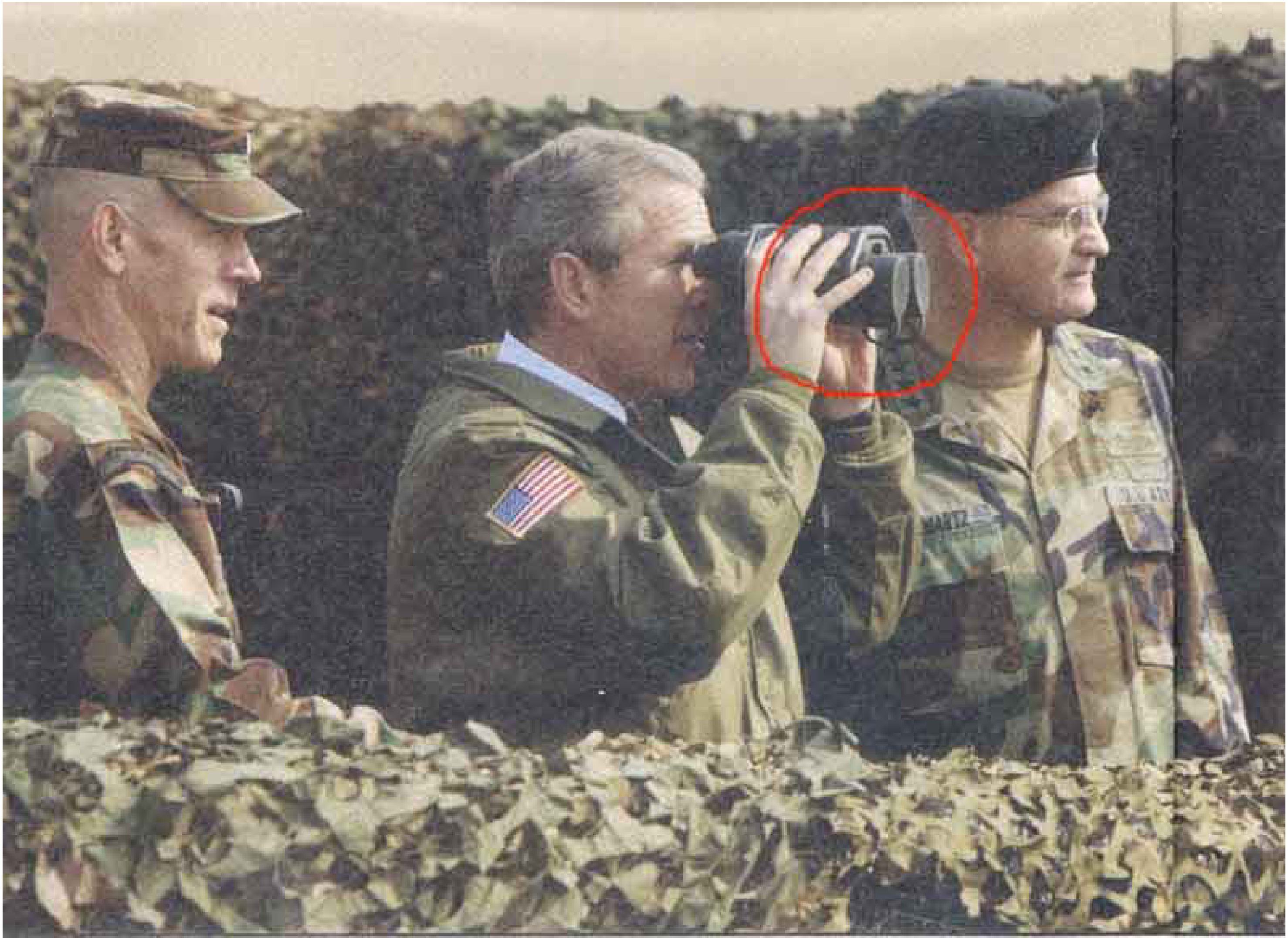


(b)
10^0
10^{-1}
10^{-2}
10^{-3}
S_{E1} (MeV−b)
0
0.5
1
1.5
2
2.5
3
E_{cm} (MeV)



Eric T. Harman

Physics Today 55:12(2002)26


MARTZ

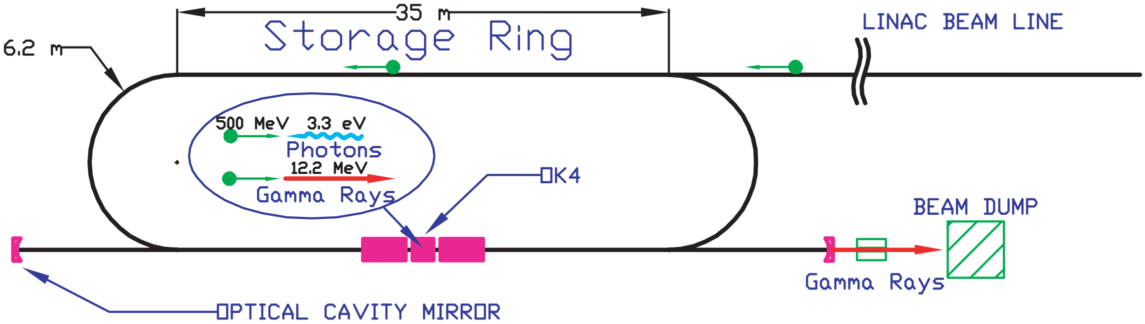
UConn - HIγS/Duke - Weizmann PTB - UHartford - GCSU - LLN Collaboration

Optical Readout Time Projection Chamber (TPC)

$$^{16}\mathrm{O} + \gamma \rightarrow \alpha + {}^{12}C$$

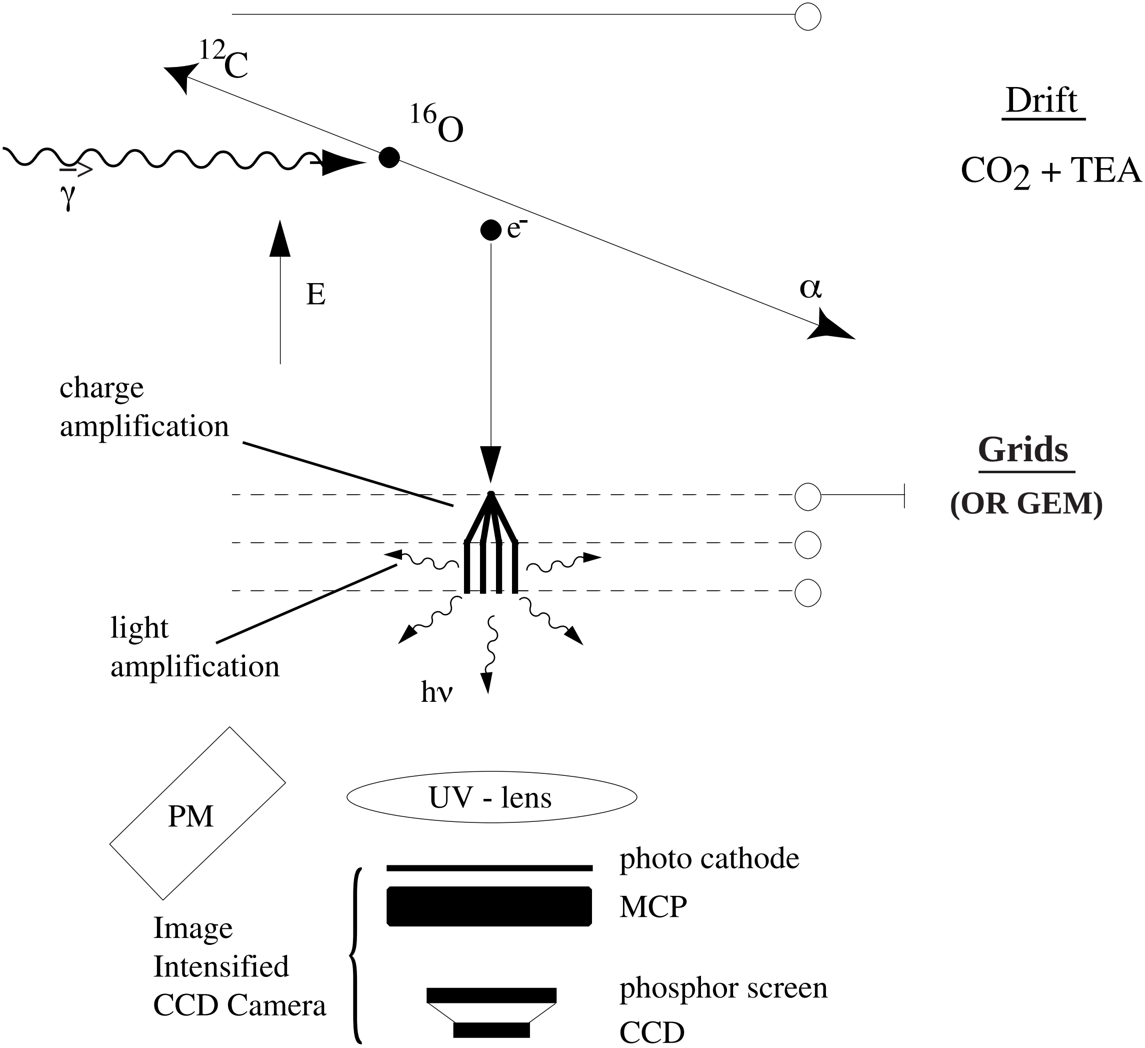
$$\mathrm{E}_\gamma \quad = 8.0 \text{ - } 10.0 \text{ MeV}$$

$$\begin{aligned}
\sigma(\gamma,\alpha) &= \tfrac{(2S_1+1)(2S_2+1)}{2(2S_4+1)} \times \tfrac{k_\alpha^2}{k_\gamma^2} \times \sigma(\alpha,\gamma) \\
&= \tfrac{1}{2} \times \tfrac{k_\alpha^2}{k_\gamma^2} \times \sigma(\alpha,\gamma) \\
&= \tfrac{1}{2} \times (80 - 160) \times \sigma(\alpha,\gamma) \\
&= \boxed{(80 - 160)} \times \sigma(\alpha,\gamma)
\end{aligned}$$



35 m
Storage Ring
LINAC BEAM LINE
6.2 m
500 MeV
3.3 eV
Photons
12.2 MeV
Gamma Rays
OK4
BEAM DUMP
Gamma Rays
OPTICAL CAVITY MIRROR

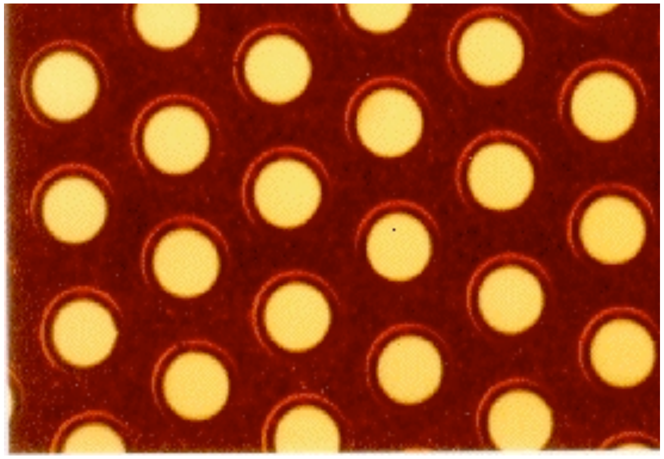
Optical Readout TPC

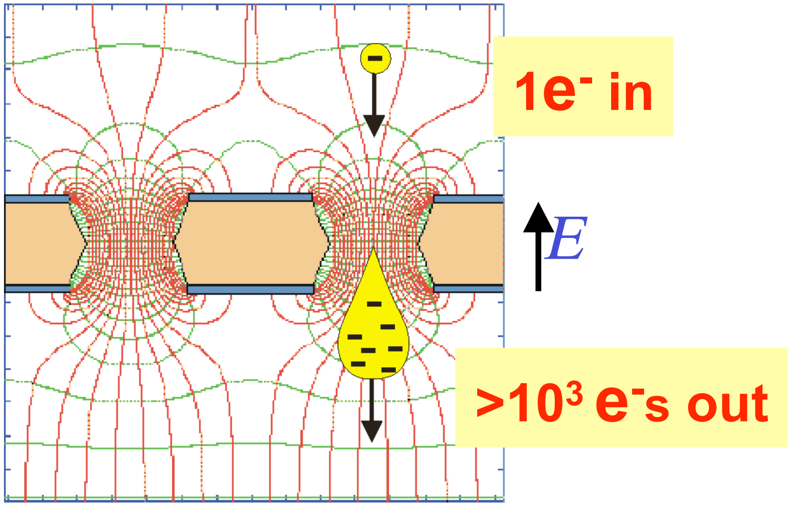


Gas Electron Multiplier (GEM)

F. Sauli NIM A 433 (1997) 531

Photo of a GEM



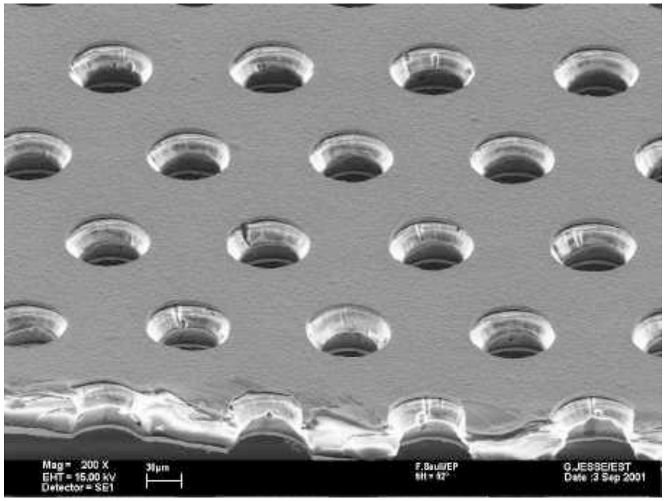


$1e^-$ in

$>10^3$ e^-s out

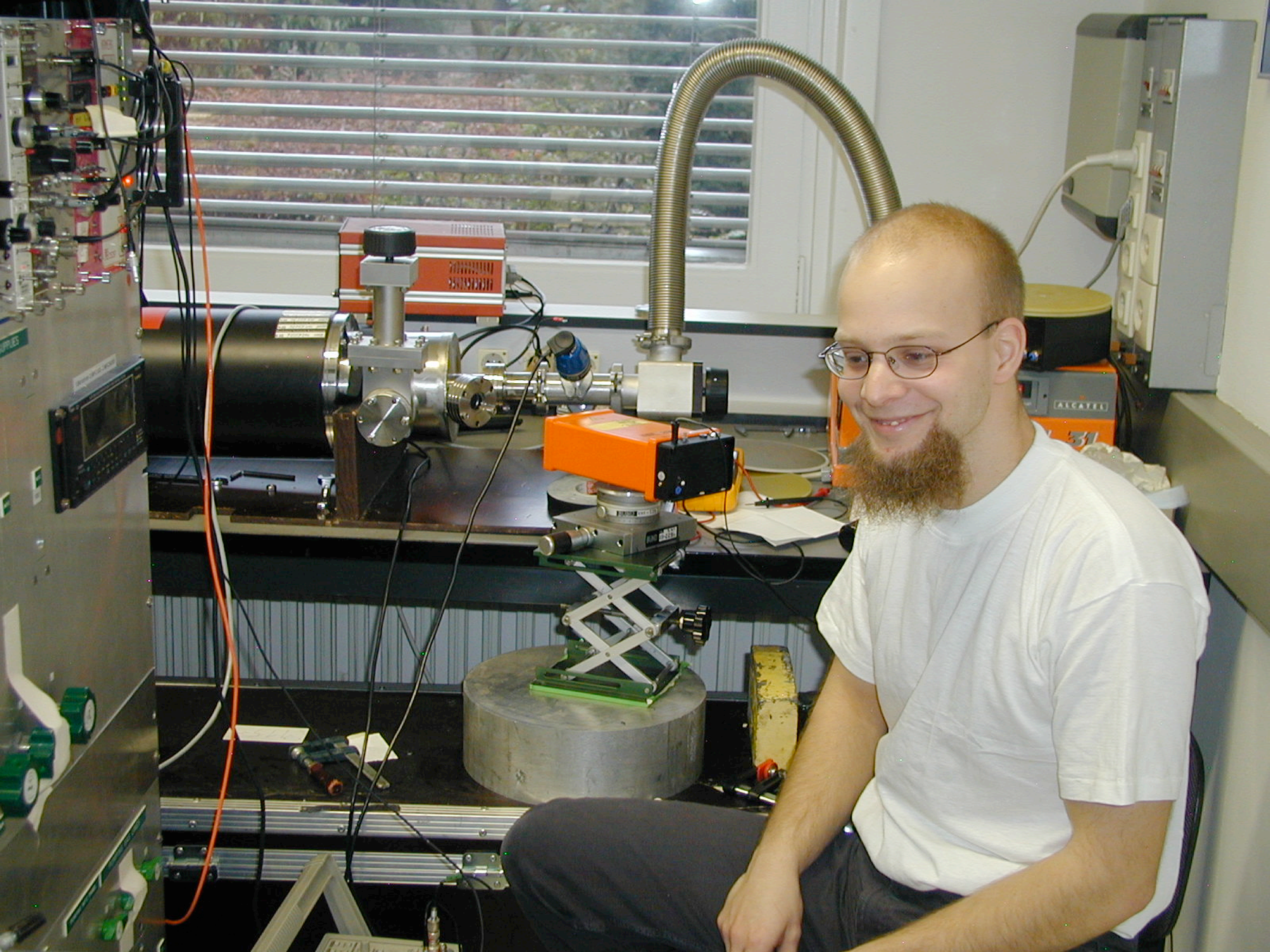
Electric field in the holes >20kV/cm

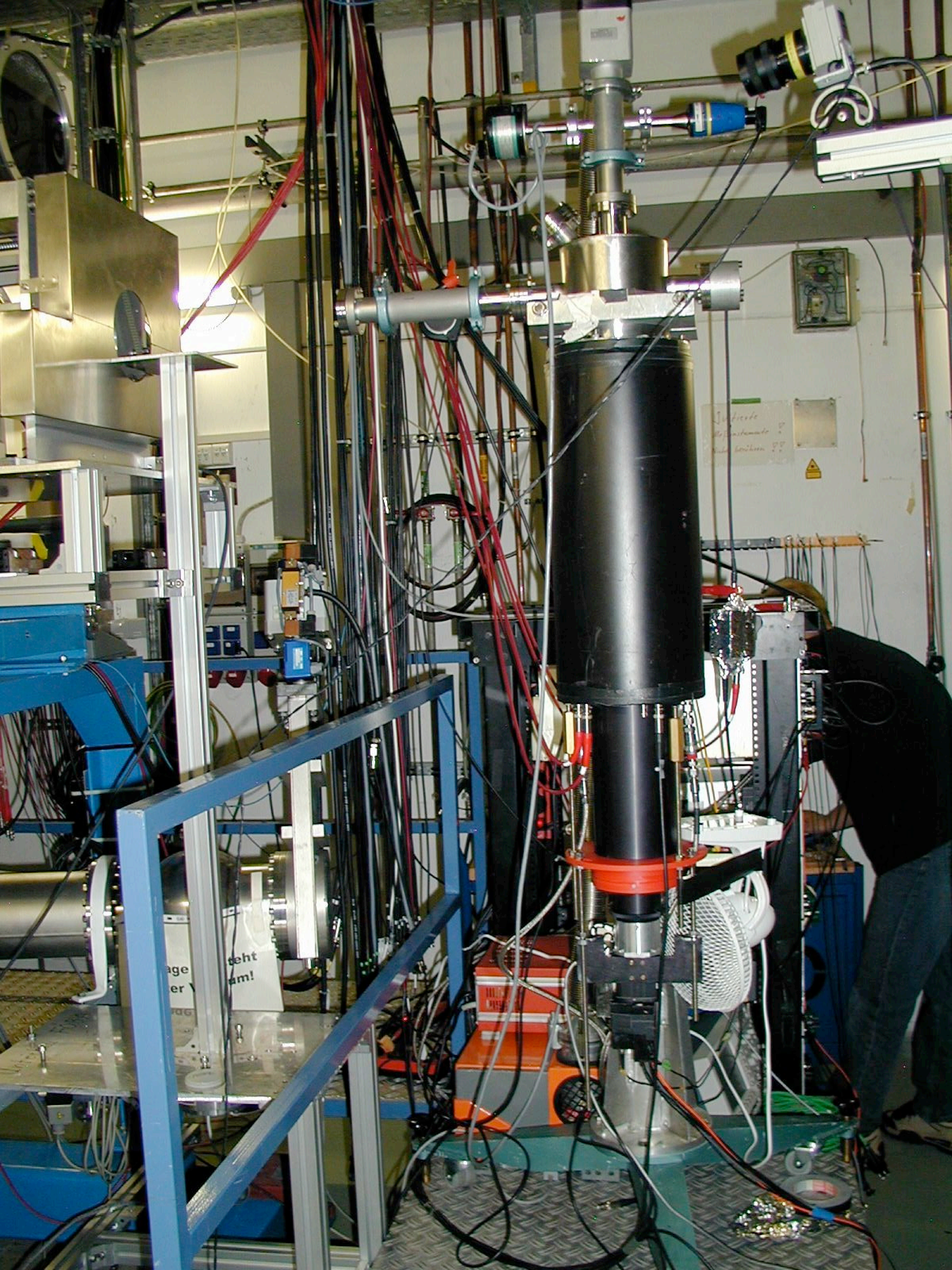
Electron Microscope view of a GEM

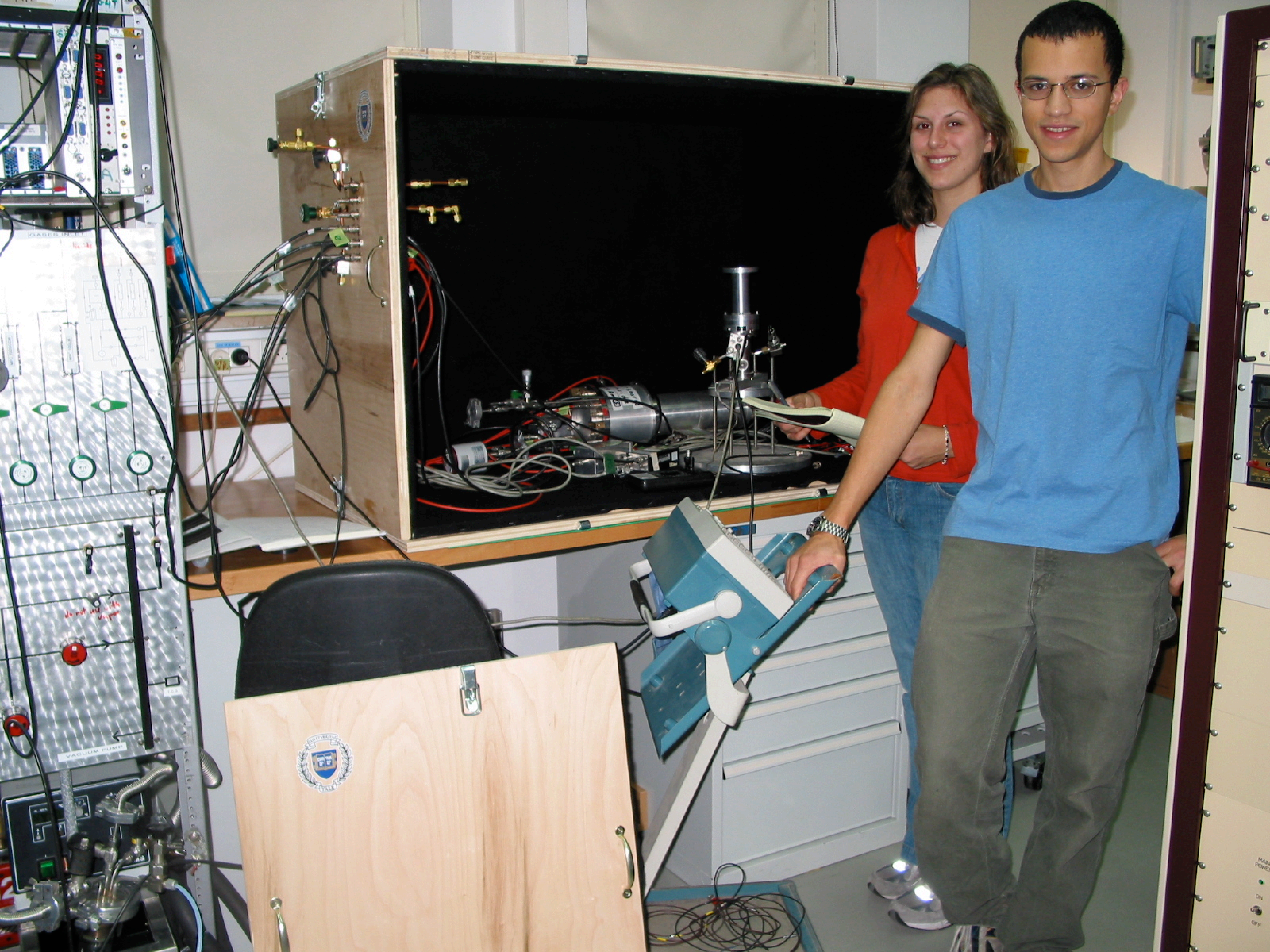


Typical parameters:

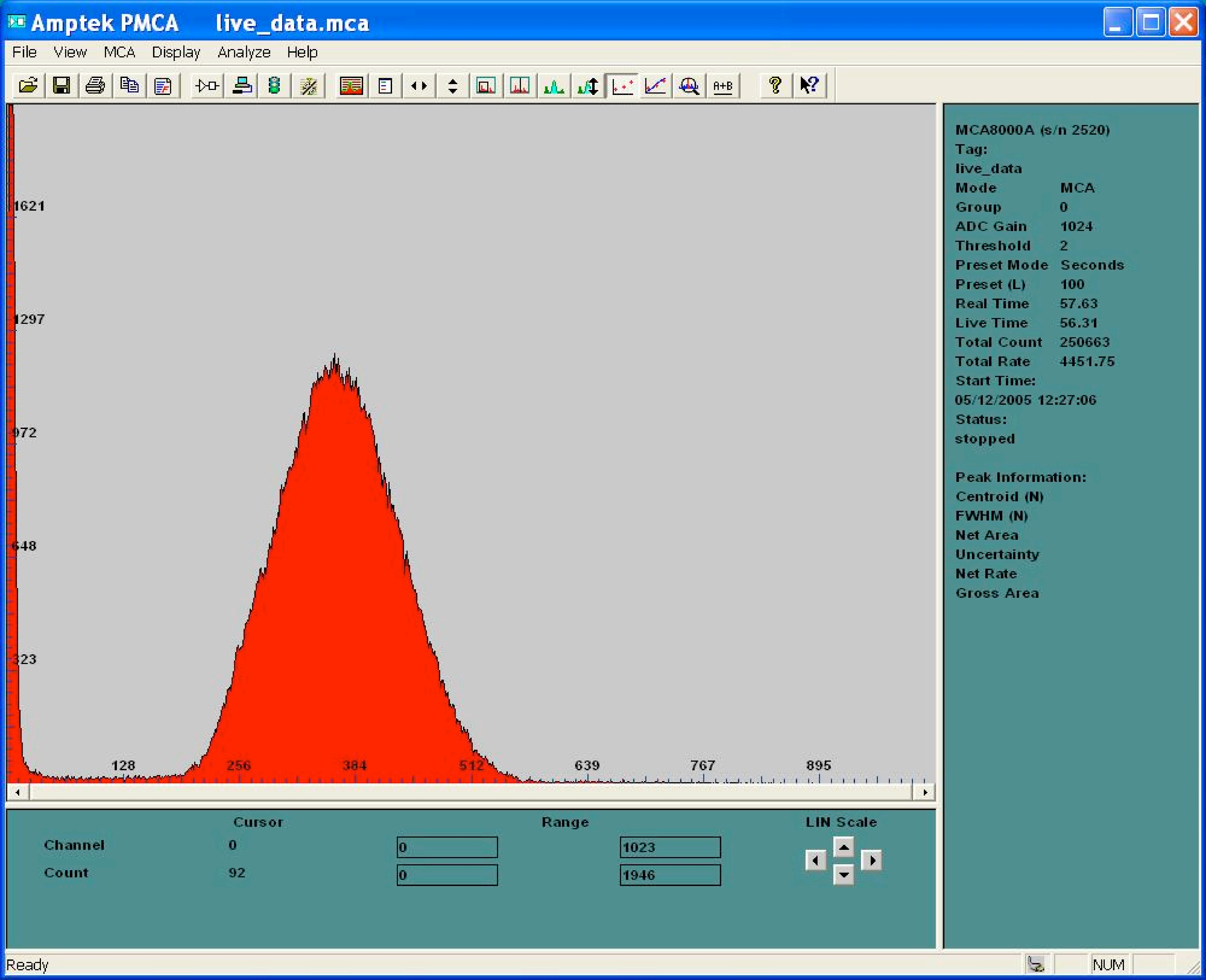
- 50μm Kapton
- metal coated
- Ø50-70μm holes
- 100-200μm pitch
- 80% opacity


ALCATEL




GASES INLET
VACUUM PUMP
ON
OFF


MODEL 205A-03R
199.0
DETECTOR
IMPORTANT NOTE
ANODE VOLTAGE
ION SOURCE
FILAMENT VOLTAGE
COLUTRON RESEARCH CORPORATION
BERTAN
ACCELERATION



MCA8000A (s/n 2520)

Tag:

live_data

Mode	MCA
Group	0
ADC Gain	1024
Threshold	2
Preset Mode	Seconds
Preset (L)	100
Real Time	57.63
Live Time	56.31
Total Count	250663
Total Rate	4451.75

Start Time:

05/12/2005 12:27:06

Status:

stopped

Peak Information:

Centroid (N)

FWHM (N)

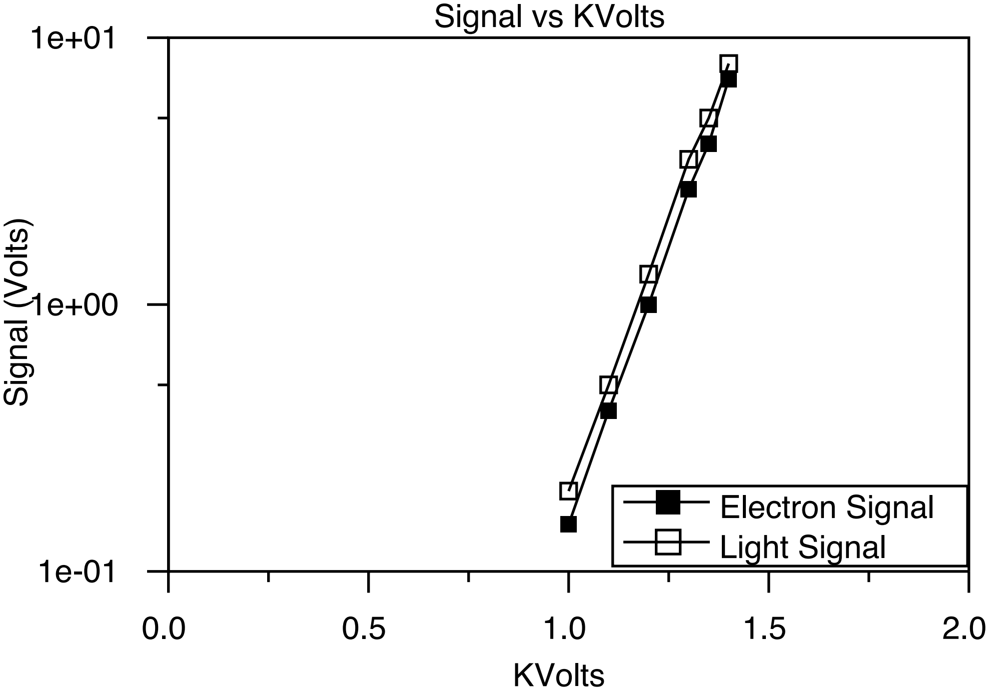
Net Area

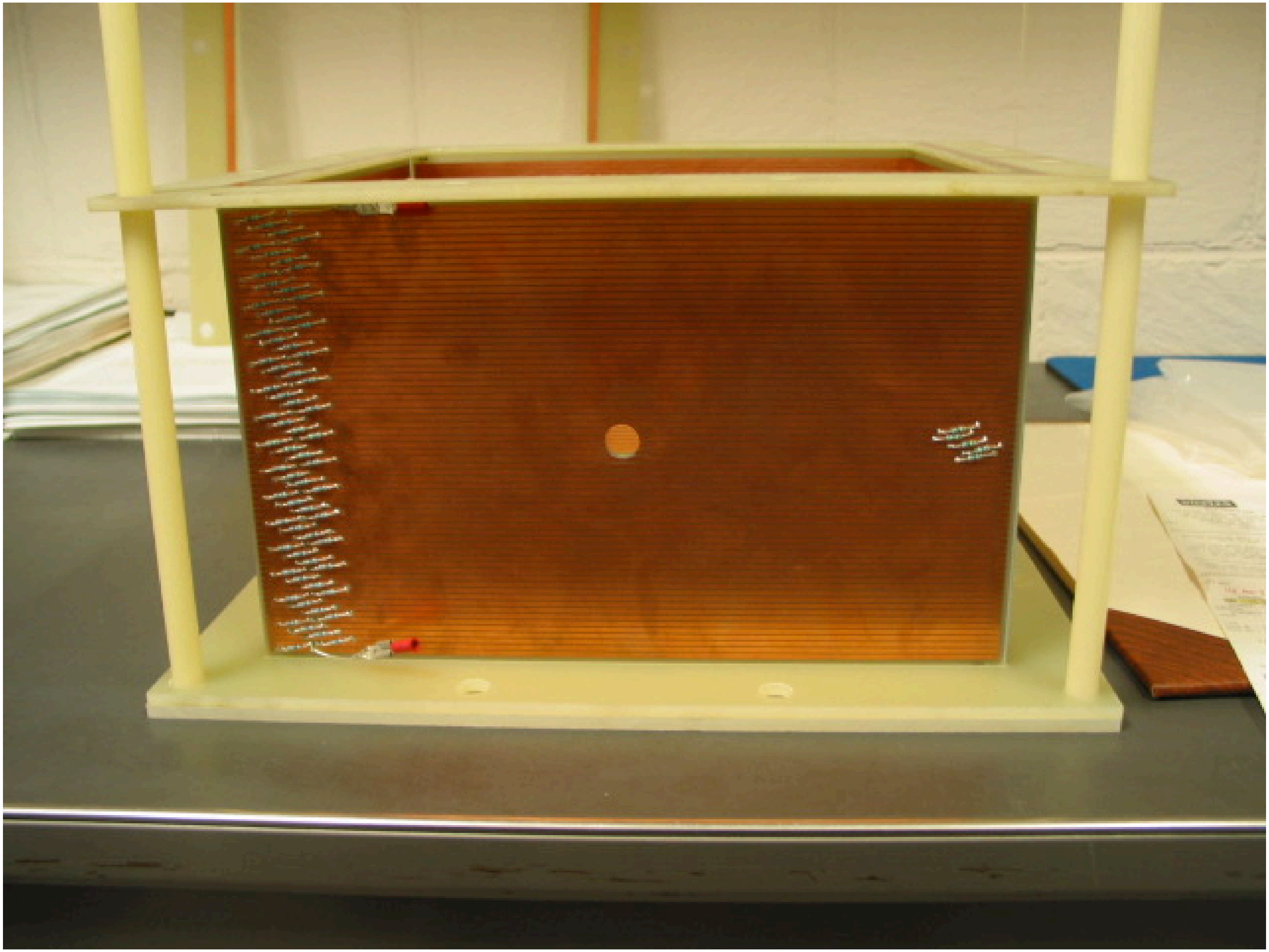
Uncertainty

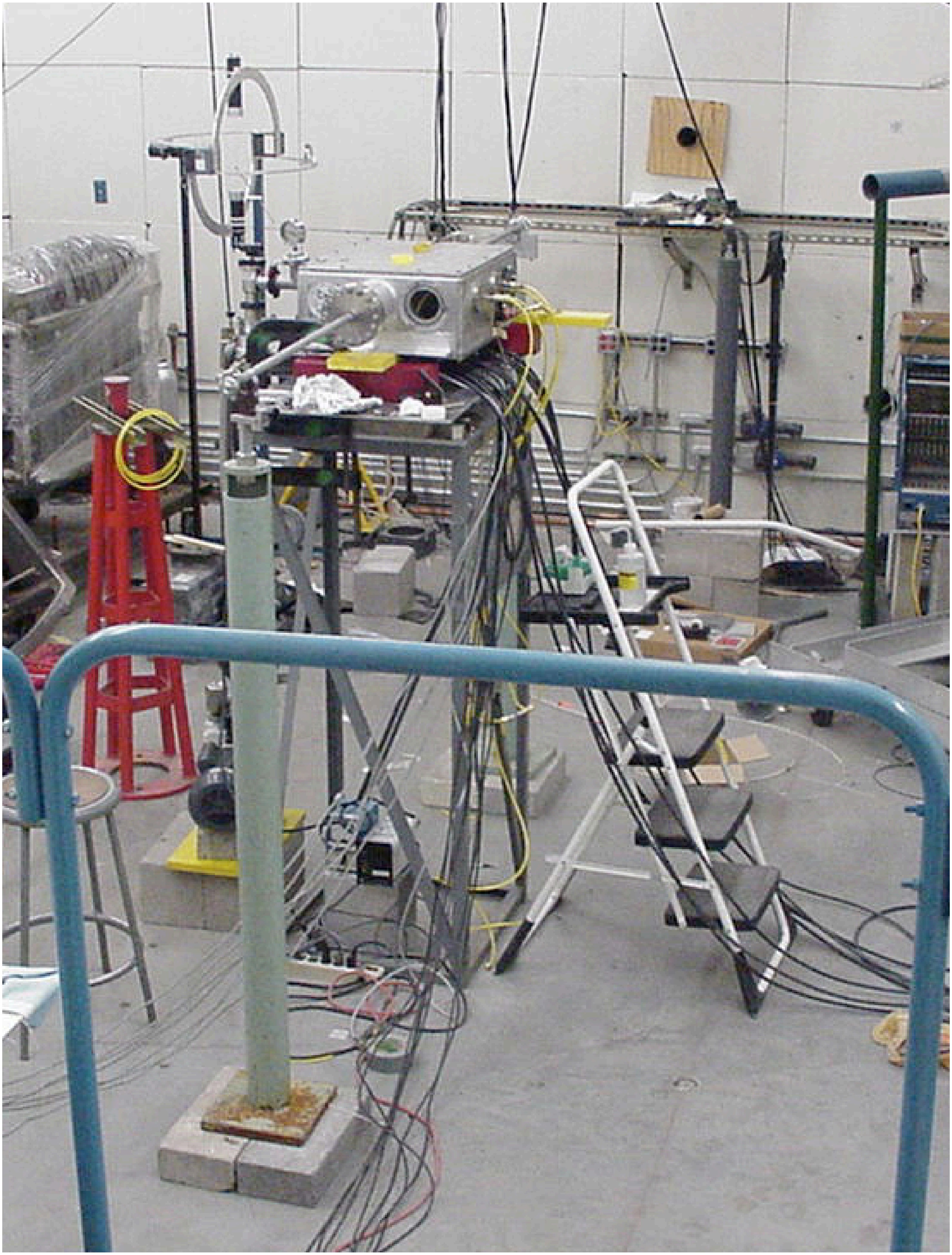
Net Rate

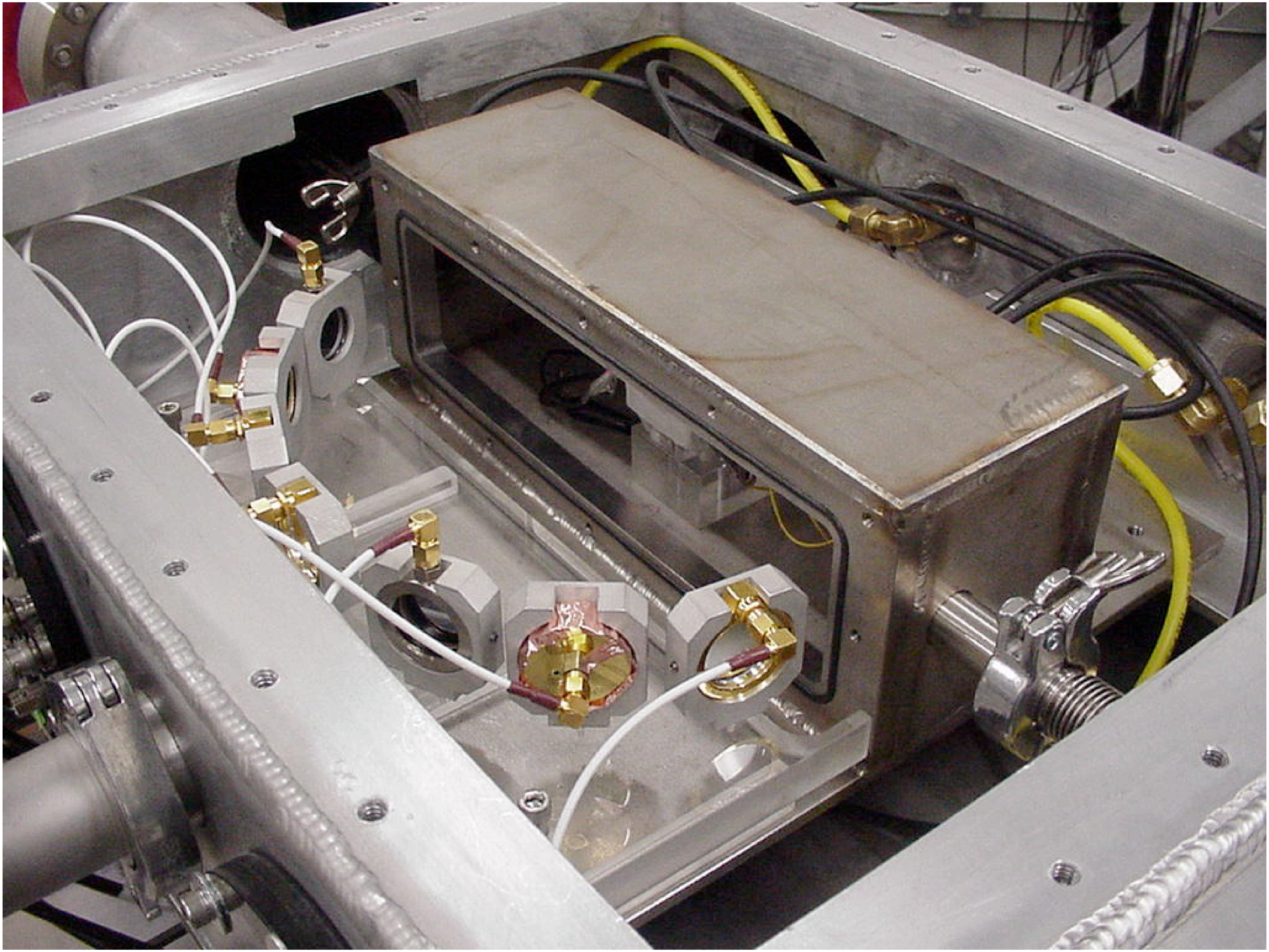
Gross Area

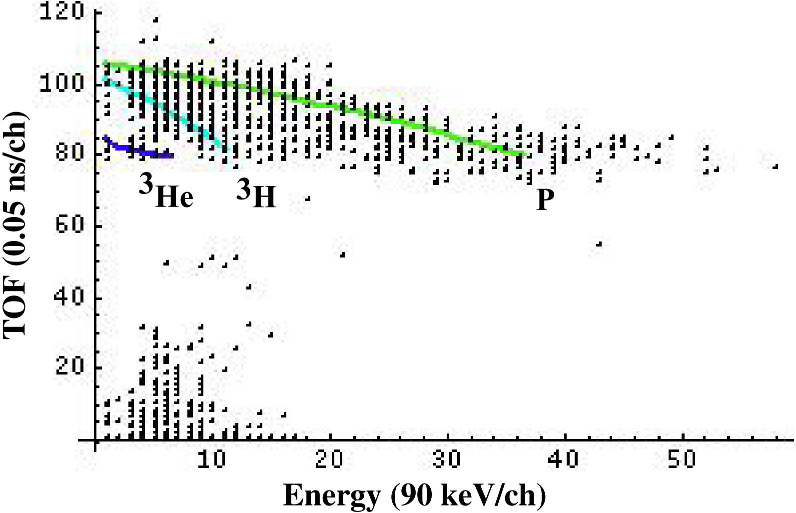
	Cursor	Range		LIN Scale
Channel	0	0	1023	
Count	92	0	1946	


Signal vs KVolts
Signal (Volts)
1e+01
1e+00
1e-01
0.0
0.5
1.0
1.5
2.0
KVolts
Electron Signal
Light Signal





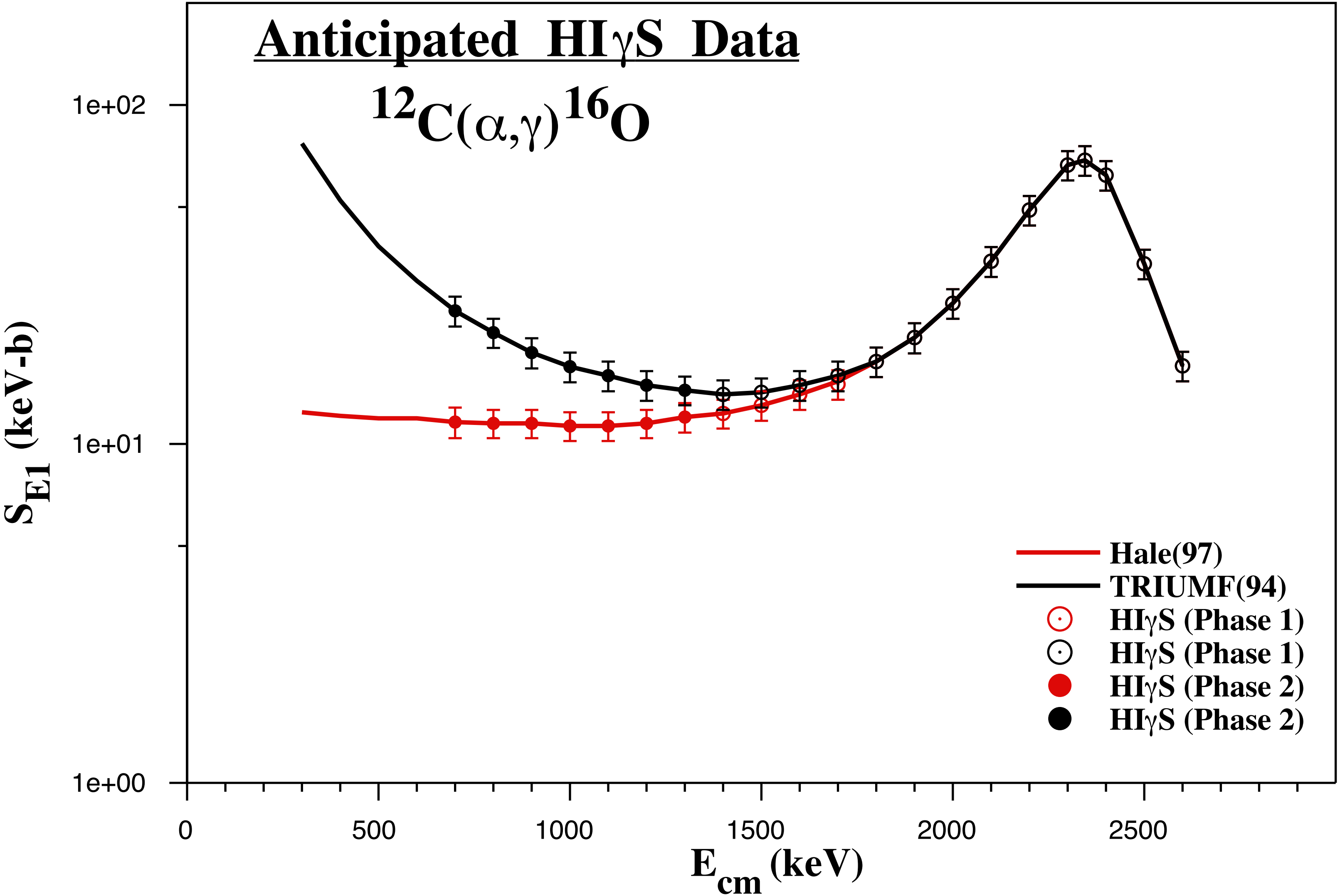


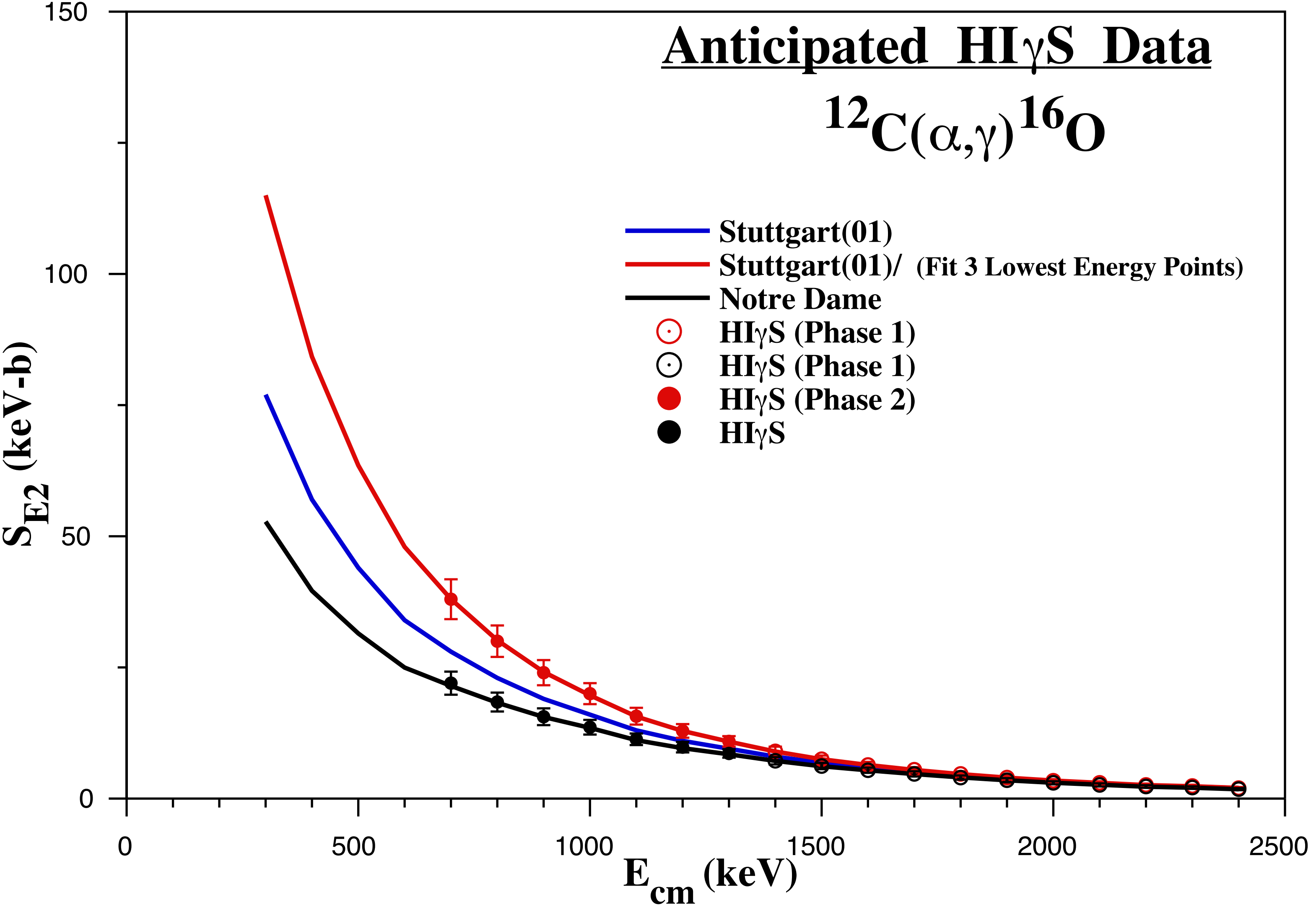


120
100
80
60
40
20
TOF (0.05 ns/ch)
^{3}He
^{3}H
P
10
20
30
40
50
Energy (90 keV/ch)

Anticipated HIγS Data

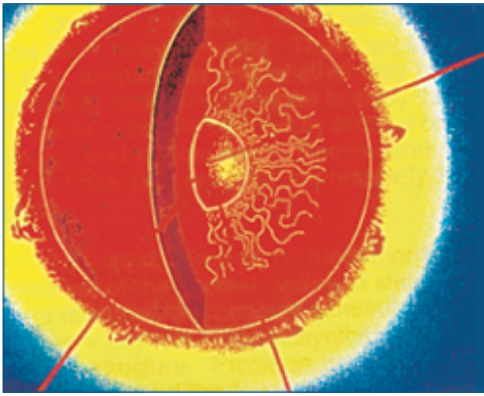
$^{12}C(\alpha,\gamma)^{16}O$





Anticipated HIγS Data

$^{12}C(\alpha,\gamma)^{16}O$



University of Connecticut
Laboratory for Nuclear Science
at Avery Point

1. **The Problem: C/O ratio in Helium Burning**
   (Who cares? the shattered hopes/illusions)

We Have a Major Problem
It is Not Solved After 30 Years
The Physics Community Cares

2. **The Solution: O-TPC**
   (Who will do it? and where?)

HIγS + O-TPC
UConn-Weizmann-PTB-Duke